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SYNDEPOSITIONAL LATERITIC ALTERATION AND CLASTIC STARVATION AS PATHWAYS IN THE FORMATION OF THE CONIACIAN OOLITIC IRONSTONES OF NORTH WADI QENA AREA, EASTERN DESERT, EGYPT

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ABSTRACT

In north Wadi Qena area, microglauabular and ooidal ironstones occur in peritidal clastic facies in the base of the Coniacian transgressive succession of the Hawashiya Formation. These ferriferous deposits are not confined to a certain state of sea level (rise or fall) where, they delineate basal transgressive facies and terminate shallower regressive assemblages. In both settings, the ironstone development is intimately related to duration of specific sedimentary dynamics, which reflect the interaction between rate of sedimentation, sediment supply and hydrodynamic regime.

The Wadi Qena ironstones comprise autochthonous and parautochthonous facies types. The former consists of welded ferriferous micromnodules and micropisoids; their fabrics and textures indicate an in situ growth from glauconite in sands and muds that exposed to a lateritic weathering during periods of sea level fall. The parautochthonous ironstones are moderately to well-sorted grainstone and packstone, composed of worn micropisoids, micromnodules and ferriferous ooids, mixed with detrital quartz. They are invariably penetrated with Skolithos and Thalassanoids reflecting a low rate of accumulation on a mobile substrate. The parautochthonous facies represent transgressive lags derived and reworked from autochthonous ironstones via effective hydrodynamic forces. The continuous reworking of ferriferous particles and the onset of ooid accretion were achieved under almost complete starvation of clastic supply, which often results with renewed marine floods.

Al-rich goethite, hematite and amorphous iron oxyhydroxides are the essential minerals and mineraloids, constituting the allochems, matrix and cement of the study ironstones. Authigenic quartz, kaolinite, calcite, gypsum and rare clots of oxidized framboidal pyrite occur in restricted and isolated patches. The enrichment of goethite and hematite with Al substantiates their derivation from lateritized glauconitic sediments.

Keywords: Coniacian, oolitic ironstone, Wadi Qena, Egypt, clastic starvation, lateritization

INTRODUCTION

Ferriferous coated grains and ooidal ironstones have been the subject of numerous scientific researches which introduced a number of genetic interpretations but with many debates (cf. Young 1989; Burkhalter, 1995; Macquaker *et al.*, 1996). Of these genetic models, a development of ferriferous ooids and pisoids in lateritic weathering environments has been documented (e.g. Parron and Nahon, 1980; Nahon *et al.*, 1980; Schwarz and Germann, 1993; Nahon, 1995). Also there is a common acceptance that the ooidal ironstones accumulated in shallow marine environments in the vicinity of landmasses with a lateritic cover and during periods of reduced sediment input (e.g. Germann *et al.*, 1987; Siehl and Thein, 1989; Mücke, 2000). This paper presents an example of microglauabular and ooidal ironstones developed from syndepositional lateritic alteration of Coniacian glauconitic clastics with subsequent reworking and accumulation during a starvation of sediment supply.

The Coniacian period in Egypt was characterized by noticeable production of ooidal ironstones (Fig.1), of which the most important and economic occurrence is at the east and southeast of Aswan (Attia, 1955; El Aref *et al.*, 1996; IEP, 1993-1997). Other equivalent occurrences, but being thinner, less economic and of different paleogeographic setting include the ironstones of North Wadi Qena area, and that reported in the Matulla Formation in west central Sinai by El Sayed (1986). Older oolitic ironstones are also recorded in north central Sinai in the Jurassic - Lower Cretaceous succession of Gebel El Maghara (El Manawi, 1986; El Sharkawi *et al.*, 1989). The youngest Phanerozoic ooidal ironstones of Egypt form the base of the Middle Eocene economic iron-ores of El Bahariya Oases, Western Desert (Said and Issawi, 1964; El Aref *et al.*, 1999; Helba *et al.*, 2001).

The Wadi Qena ironstone is reported for the first time by Hendriks *et al.* (1987) in their regional lithostratigraphic description of the Upper Cretaceous succession of SE Egypt. Since that time, this ironstone has never received any geological or mineralogical investigations. The present study demonstrates the stratigraphic setting and sedimentological aspects of these ironstones and the hosting sediments. It elucidates their essential mineralogical and chemical composition as well as the distinct fabrics and structures that reflect the impact of the depositional and diagenetic (lateritic) processes and conditions on the mode of ironstone formation.

Two stratigraphic sections, representing the ironstone intervals have been measured and sampled (Fig.2). Representative thin sections and polished samples are prepared and petrographically inspected by the polarized and reflected light microscope. The petrographic identification of minerals is confirmed by XRD analysis. Polished thin sections are prepared for microprobe analysis, which was carried on some traverses of different ferriferous-coated grains and on pore-filling substances. The chemical compositions of the different ironstone facies types are obtained by XRF analysis.

STRATIGRAPHIC FRAMEWORK

The study ironstones occur in the Hawashiya Formation (Late Turonian - Coniacian), which is a part of a thick Cretaceous succession forming the western bank of the N-S trending Wadi Qena (Fig. 2). Such bank is in the form of questas dipping gently due west and are dissected by the upstream branches of Wadi Hawashiya and Wadi Um Omiyed. The history of Wadi Qena and the stratigraphic evolution and subdivisions of its Cretaceous sedimentary record have been studied by many authors (e.g., Said 1962, 1990; Hendriks *et al.* 1987 and Klitzsch *et al.* 1990).

At the study area, northern part of Wadi Qena (Fig.2), the Hawashiya Formation attains a thickness of about 178m, and overlies unconformably the Turonian Um Omiyed Formation and rests conformably below the Campanian Rakhiyat Formation. The Formation is built up of heterogeneous lithologies including quartzose sandstone, glauconitic sandstone and mudstone, fossiliferous limestone and marl with several coquina beds. Some of the fossiliferous marl horizons yield abundant species of the Coniacian ammonites as *Metatissotiaourneli*, *M. ewaldi* and *Subtissotia africana* (Hendriks *et al.* 1987). The Hawashiya facies are almost of marine origin, grading from inner shelf to backshore, except the basal facies interval being of fluvial affinity. According to Hendriks *et al.* (1987), this formation is formed of four main sedimentary sequences of alternating regressive and transgressive facies successions (Fig.3). These are:

1. Lower regressive (fluvial) sequence (LRFS), 9.5m thick.
2. Lower transgressive (inner shelf-shoreface) sequence (LTFS), 54m thick.
3. Upper regressive (shoreface-backshore) sequence (URFS), 30m thick.
4. Upper transgressive (inner shelf-shoreface) sequence (UTFS), 76m thick.

The concerned ironstones are confined to the basal part of the lower transgressive sequence (Fig.3). This sequence consists almost entirely of open marine clastic- and carbonate- facies representing tidal flat to inner shelf deposition. They are accumulated during the widespread transgression of the Coniacian Sea that advanced southward to Aswan - Abu Sumbul district where it deposited the equivalent ironstone-bearing marine clastics of the Tamsah Formation of El Naggar (1970). In the basal part (~10m thick) of this sequence, the ironstones occur in two principal stratigraphic units, assigned "lower and upper ironstone-bearing units (Fig.3), separated by glaucony rich sandstones and mudstones. The ironstone-bearing units (~2-3m thick for each) consist of thin- to thick (5 -50 cm) oolitic and non-oolitic ironstone bands intercalating with glauconitic- and ferruginous sandstones.

SEDIMENTOLOGIC FRAMEWORK

The Hawashiya ironstone-bearing interval, up to 10 m in thickness, is formed entirely of siliciclastic facies comprising glauconitic sandstones and sandy mudstones. These glauconitic clastics stack in small-scale shoaling-upward cycles (0.5-1.5 m thick) that commonly terminate with sandy and glauconitic ironstones (microglauconitic and oolitic) showing different degrees of subaerial lateritic alteration (Fig.3). In most cycles, the vertical transition from proper glauconitic clastics to glauconitic ironstone is gradational and commonly with gradual increase in the glauconite grains and matrix, which in turn display an upward advance in their alteration and enrichment with iron (Fig.4). On the other hand, the contact between the successive cycles is sharp and almost erosive, with either basal reworked ironstone facies or with basal ferruginous sandstones containing rip up ironstone clasts. The following is a description and sedimentologic interpretation of the different recognized facies.

1. Glauconitic sandstone facies (GSF)

Description

It is the essential facies of the study ironstone-hosting interval and forms the basal to middle parts of the shallowing upward cycles (Fig.3). Its beds are thin- to very thick (10-50 cm thick), commonly have sharp planar to scouring soles and non-erosive to rippled tops. They are internally massive or, in parts, show ripple cross- and flaser-laminations and occasionally are horizontally bioturbated. Glauconitic and ferruginous mud concentrates in flaser laminae occupying the ripple troughs. Some of the erosive soles contain scattered rip-up clasts of ironstone. The rock is pale yellow to pale green, commonly with brownish and reddish tarnish. It is fine- to medium- grained, and moderately- to well-sorted with scattered coarse sandy grains (Pl.1a). It consists mainly of quartz and glauconite occurring in almost equal proportions but in different distributions, where in some microscopic pockets or laminae the glauconite predominates, while in adjacent pockets, the quartz is more pervasive (Pl.1a). Scattered skeletal phosphates (shark teeth and bones) being of iron-stained isotropic

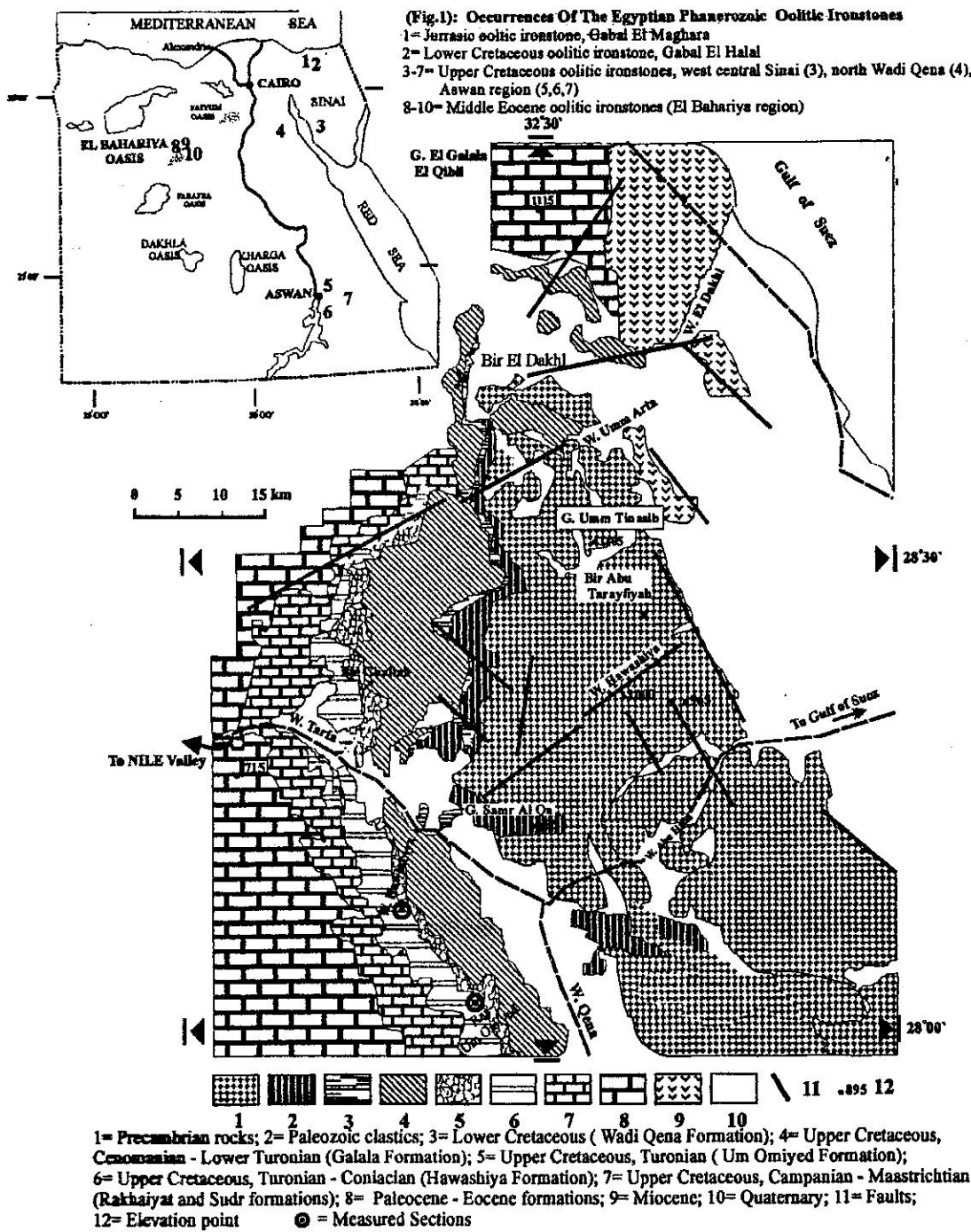
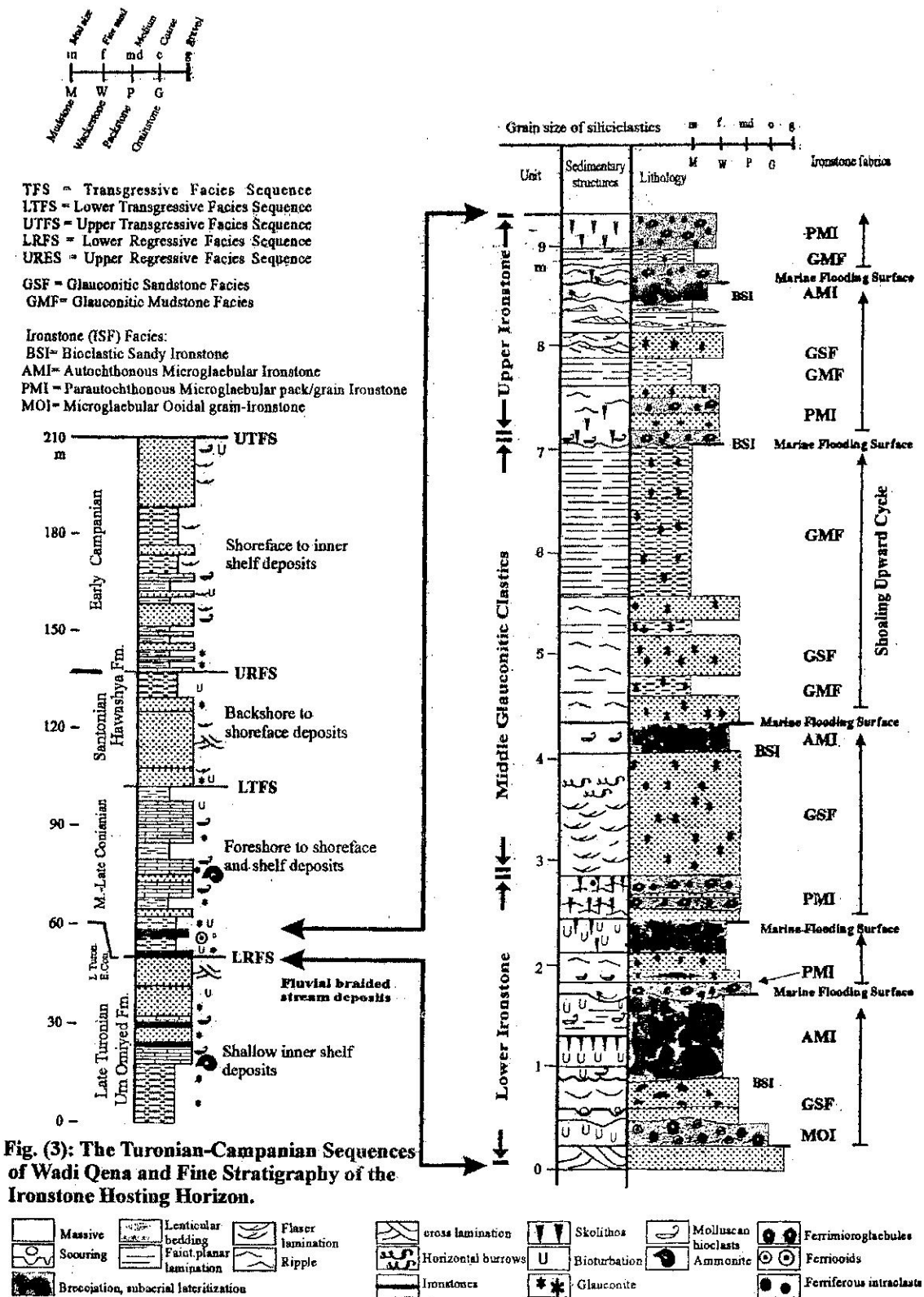
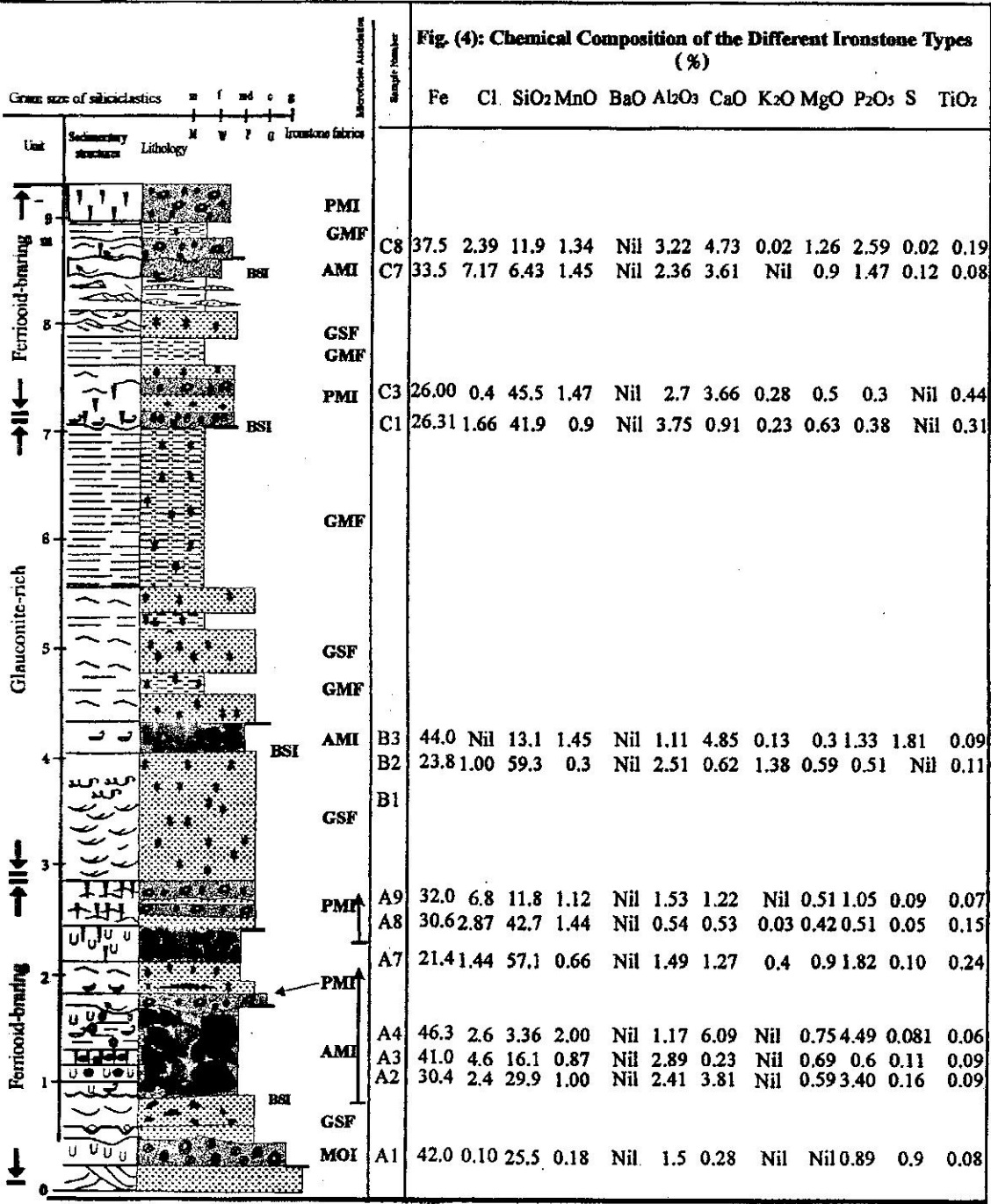


Fig. (2): Geological Map of North Wadi Qena Area Showing the Measured Sections of the Studied Oolitic Ironstone (Modified After the Geological Map of Egypt, Conoco, Klitzsch *et al.*, 1987 and Abdallah *et al.*, 1992).





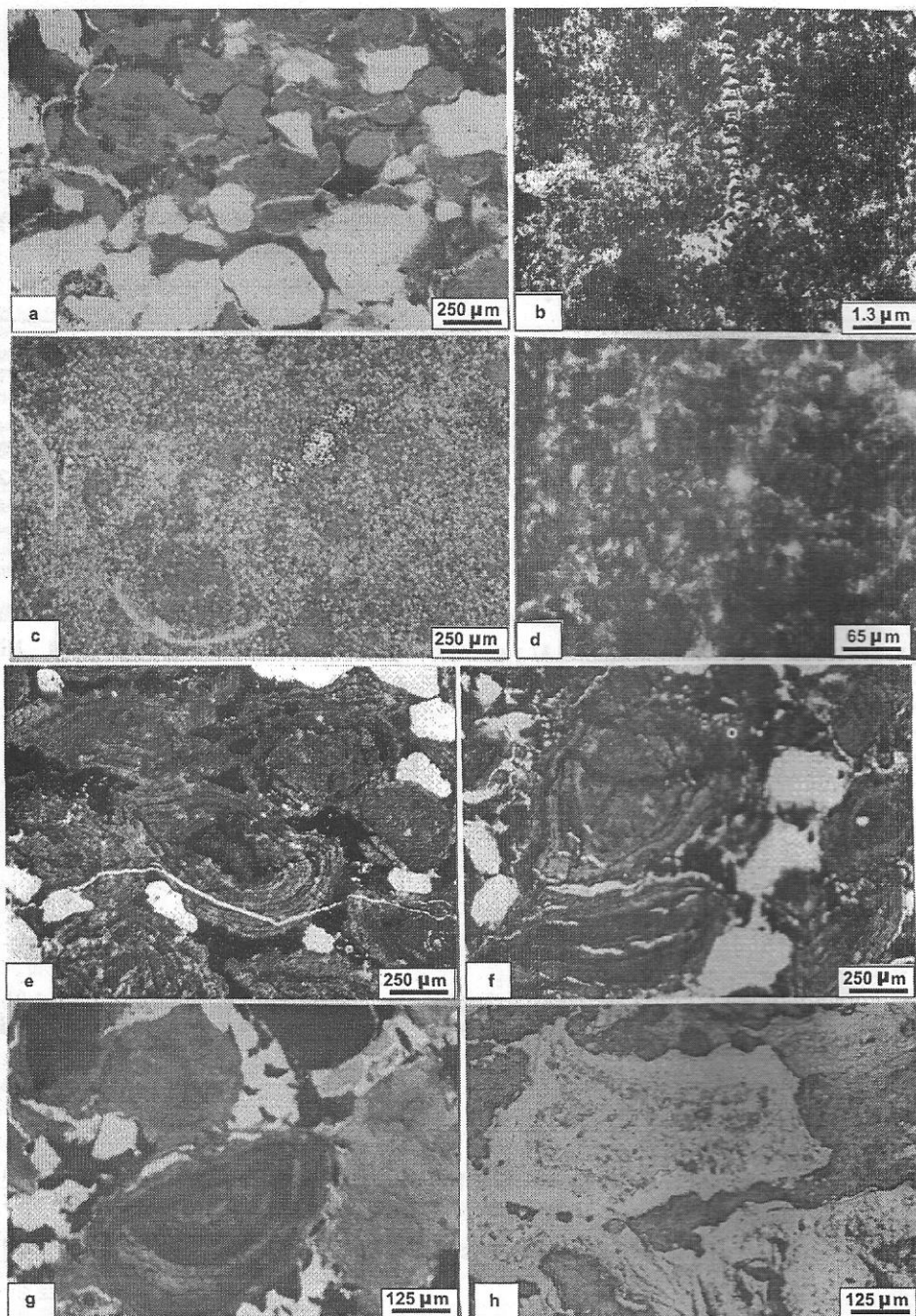


Plate 1

(a): Glauconite and quartz grains in a nearly equal proportion and different distribution in GSF. Notice the close fitting of the *in situ* dissected glauconite giving fitted angular grains, Plane Polarized Light (PPL). (b): Microscopic trace of vertical biogenic tube penetrating the BSI facies (PPL). (c): Scattered delicate bivalve shells and clusters of oxidized framboidal pyrite in BSI facies (Polished sample, PPL). (d): A cryptocrystalline limonitic groundmass with coalesced circular and polygonal crystallites of goethite and hematite in BSI facies, Crossed Nicols (CN). (e): Anastomosed and welded ferriferous micromnodules, micropisoids and intraclasts with frequent alveolar voids and some detrital quartz in AMI facies (PPL). (f): Triangular ferriferous micropisoids (with oosepic) and micromodule (massive) separated by circum peripheral cracks and aligned nearly parallel to their long diameters (PPL). (g): Microunconformity with onlapping relationship between cortical zones in a ferriferous pisoid, AMI facies (PPL). (h): Thick bright goethite laminae being developed in the expense of the dark amorphous iron laminae and cores of the ferriferous micropisoids, AMI facies (PPL).

collophane, as well as few grains of plagioclase, microcline, biotite, muscovite, zircon and rutile are also encountered. The quartz grains (40-60% of the rock) are mostly angular to subrounded, and are either partially corroded, embayed or intensively digested by the surrounding glauconitic clay matrix or iron oxide cement. Many of the grains are outlined by very thin rind of iron-stained clays and few grains display worn silica overgrowth, reflecting recycling. The glauconite almost occurs as angular to subangular grains, and occasionally has rounded to subrounded oval form (Pl.1a). Most of the adjacent grains are surrounded and separated from each other by open straight, branched and curved cracks. The protruded and recessed grain borders of the adjacent glaucony grains display a close fitting to each other (Pl.1a). These fitted grains range, in size, from fine to coarse sand, and are internally massive with pale yellowish green colour. Some of these grains are partially stained with iron and some others are intensively transformed into minute crystals of goethite and hematite.

Interpretation

The glauconitic sandstone beds and their characteristics (the sharp to scouring soles, massive- to flaser-laminated structures and non-erosive rippled tops) indicate accumulation under a decelerating vigorous flow of probably storm-induced currents (Kumar and Sanders, 1976). The erosive soles with rip-up ironstone clasts represent the erosional product and lag-accumulation during the height of the storm. As the storm waned, the sand grains firstly dropped from turbulent suspension and latter accumulated and rippled via fair- weather waves or currents action (Simpson and Eriksson, 1990). Under the intermittent slack water periods, the suspended iron-bearing clays and colloids settled down, infiltrated as a matrix and /or accumulated in discontinuous pockets or flaser laminae drapping the sand ripple troughs. Similar storm-related sandstone facies are described from near-shore, shoreface and shallow shelf environments (Kumar and Sanders, 1976; Soegaard and Erikssons, 1985). The paucity of fauna in this facies and its upward gradation into sandy glauconitic ironstones containing abundant nearshore echino-fossils of *Skolithos* and *Thalassanoids* may substantiate the deposition in the lower to middle intertidal flat (Fig.5).

The non-pelletal and angular form with distinct polygonal fitting and reciprocal contacts of the glauconite in this sandstone facies may suggest its autochthonous formation and *in situ* fragmentation. However, the occurrence of autochthonous glauconite in that near shore sandstone facies does not fit with the general idea that restricted the formation of authigenic glauconite minerals at depths greater than 50m, almost in mid shelf to slope environments (Bremner and Willis, 1993 and Amorosi, 1995). Recently, Chafetz and Reid (2000) disputed the generalization of this concept at least for glauconitic minerals in the ancient rock record. They (op.cit.) substantiated the precipitation of autochthonous glauconite in the Paleozoic tidal flat to shallow shelf clastic sediments.

2. Glauconitic mudstone facies (GMF)

Description

This facies occurs in the middle and upper units of the study ironstone-bearing interval (Fig.3). It constitutes a very thick bed reaching in thickness to about 1.5 m as well as thin to medium beds (10-25 cm thick) that intercalate with the glauconitic sandstone facies forming together coarsely interlayered-, lenticular-, and flaser-bedding. The mudstone rock is pale green to grey in colour with occasionally pale brown patches. It is glauconitic with thin streaks of fine sand and silt. The beds are internally massive to faintly laminated, and are barren of megafossils and biogenic structures.

Interpretation

This mudstone facies represents mid- to upper- tidal flat deposits. Its fine-grain size and faint laminated nature as well as its occurrence as flaser laminae in the sandstones indicate sedimentation from suspension in quiet or slack water. On the other hand, the laminae and discontinuous lenticles of sands and silts within the mudstone represent sporadic bed load sedimentation via short-lived storm or tidal currents. Flaser and lenticular bedding are distinctive depositional structures in mid-tidal flat environment (Reineck, 1975; Weimer *et al.*, 1982).

3. Ironstone facies (ISF)

The ironstone facies occur in the lower and upper parts of the study siliciclastic interval (Fig.3). They are invariably sandy with variable amount of quartz and glauconite grains. Their framework composition comprises ferriferous microglauabules (nodules and pisolitic concretions), intraclasts, and ooids. These ferriferous allochems differ in their proportion from bed to another, and are almost embedded in a matrix of oxidized glauconite and amorphous iron-oxyhydroxides associated with authigenic goethite and hematite. Based on the type of dominant ferriferous particles as well as the depositional and diagenetic fabrics, the ironstone facies are differentiated into four subfacies types (Figs.3&5).

3.1 Dioclastic sandy mud- to wacke-ironstone (BSI)

Description

This ironstone facies type (23- 30% Fe, Fig.4) forms thin beds and laminae (5-15cm thick) that commonly rest upon and interlaminates with the ferruginous glauconitic sandstone facies (Fig.3). The beds are faintly laminated

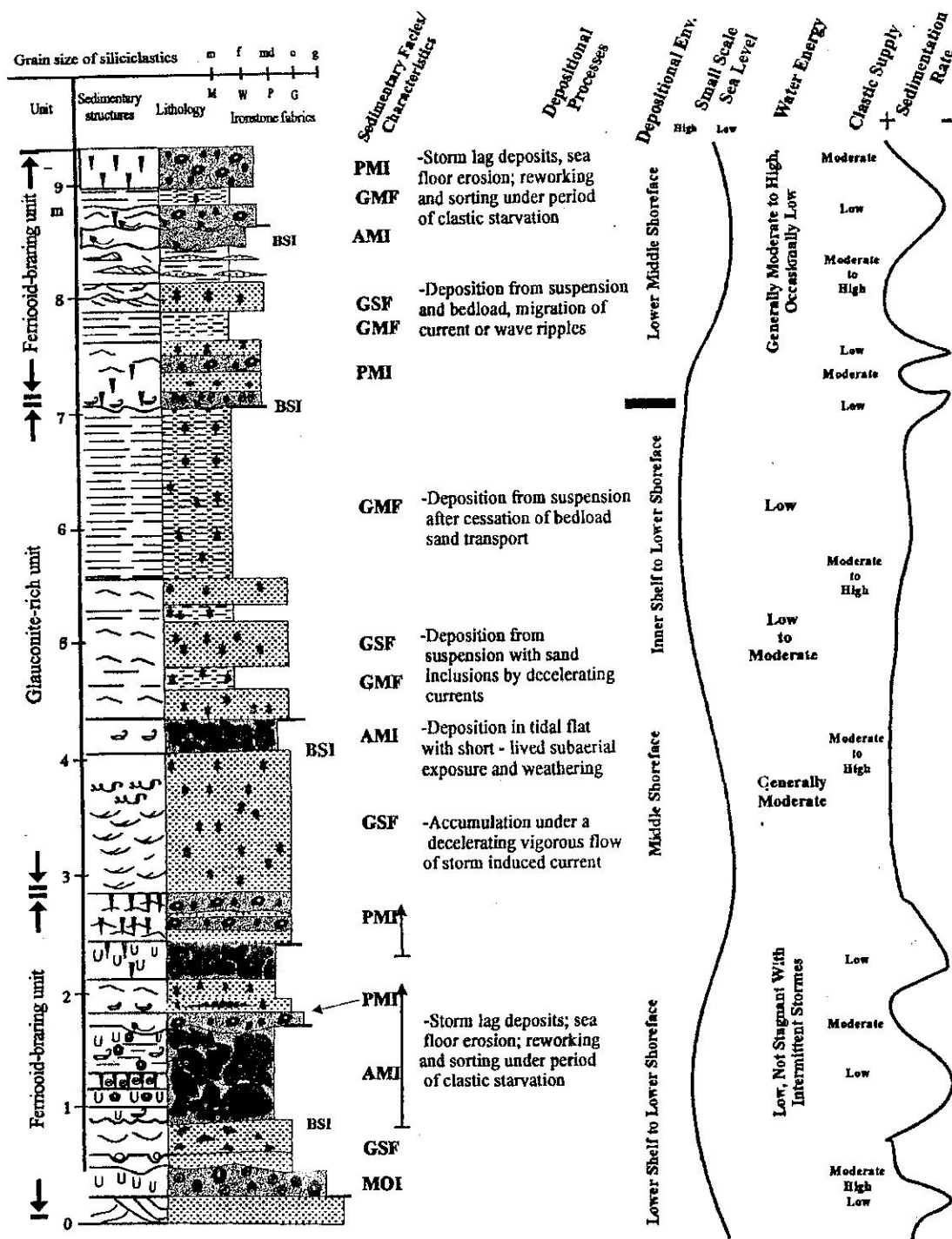


Fig. (5): Sedimentary Facies, Depositional Processes and Mechanisms and Depositional Environments of the Study Ironstones

but commonly penetrated by short vertical tubes of *skolithos*, their traces could be also observed in the microscopic scale (Pl.1b). The rock is mottled brown and mud-supported. It is composed of open packed scattered quartz grains (30-40%) with some partially oxidized and iron-stained glaucony grains (5-20%) as well as disarticulated valves of pelecypods and occasionally ostracods (Pl.1c). These terrigenous grains and fossil valves are set in yellowish to dark brown ferruginous groundmass. The quartz grains are angular to very angular and grade in size from silt to medium sand. Such textural parameters of wide spectrum grain size and angularity are subtle and seem to be intimately controlled by the intensive corrosion and replacement of quartz by the surrounding ferruginous matter. The observed glauconite grains, which are also very angular and of silty to medium sandy size appear to represent remnants of probably much higher content of glauconite of which a considerable portion was completely oxidized and transformed into iron-oxides and hydroxides. The pelecypod and ostracod fossils in this facies are very less diversified. Almost all original valves are completely dissolved and their mouldic cavities are either empty or being mostly occluded with fibrous chalcedonic quartz and calcite. Some casts and/or moulds are filled with surrounding ferruginous matter containing some quartz and yellowish green glauconite grains.

The ferruginous groundmass consists of pale to honey yellow cryptocrystalline or amorphous iron compound (limonite mixture), containing abundant separate or most commonly coalesced crystallites of goethite. The latter displays bright orange to less commonly blood red colours and characteristic circular to polygonal shape (Pl.1d). They are almost outlined by a brown rind of amorphous iron giving a network pattern or in some places possess dot-like dark cores. Ghosts of greenish yellow glauconite showing aggregate polarization pattern, as well as, clusters of oxidized framboidal pyrite are not uncommon within this limonitic groundmass (Pl.1c).

Interpretation

The mud-supported fabric and the overall fine-grain size of this sandy mud-ironstone facies indicate deposition in relatively quiet shallow water being interrupted by incursions of sand grains through sporadic storm or fair weather currents or by advancing and receding tides (Fig.5). The penetration of the facies with short *Skolithos* tubes and its paucity of diversified fauna reflect a rather mobile- and very shallow substrate, slow rate of sedimentation and unfavorable ecological conditions (Weimer *et al.*, 1982). These depositional conditions as well as the types of ichno- and body-fossils are common in the intertidal flats, particularly the mud flats (Frey and Pemberton, 1985). According to Prothero and Schwab (1996) the mud- flats can harbor oysters and other organisms that can not tolerate the strong flow of the lower tidal flats. The pervasive transformation of the original glauconitic mud into iron oxide and hydroxide minerals may reflect aerobic conditions in the mud-flat sediments and may confirm the slow to non-sedimentation regime. The oxidizing medium may result through the abundant *Skolithos* borings or during the current exposure of the mudflats in the periods of low tides.

3.2 Autochthonous microglauabular ironstone (AMI)

Description

It is the essential and the most common ironstone type (21-44% Fe, Fig.4) in the study ironstone-bearing interval. It overlies, with a gradational contact, the bioclastic sandy wacke/mud-ironstone or glauconitic sandstone, and is scoured by the allochthonous microglauabular pack/grain-ironstone facies (Figs.3&5). The rock is yellowish brown in colour and nodular or boudinage in geometry with internal laminae or crusts of dark brown iron oxides.

Petrographically, this facies is sandy, porous and is formed of anastomosed and welded ferriferous microglauabules and intraclasts enclosing in-between scattered quartz grains and frequent alveolar voids (Pl.1e). The microglauabules comprise micronodules (internally structureless) and micropisolithic concretions displaying an internal concentric structure (oosepic structure, sensu Nahon *et al.*, 1980). Although many of the adjacent micronodules and micropisoids are separated by circum-peripheral cracks (Pl.1f), they are mostly aligned with their long diameters are nearly parallel, except few being deviated and disoriented (Pl.1e). The microglauabules have mostly elliptical, triangular and discoidal shape and less commonly being circular (Pl.1e). The micropisoids range, in type, from those with large massive core and thin cortex to completely concentric micropisoid with/without very reduced nucleus. All intermediate types between these two end members are observed. In most types, it appears clearly the hazy and gradational nature of the contacts between cores and surrounding cortical laminae (Pl.1e&f). Almost all cortices consist of an alternation between discontinuous and interfingering bright orange to honey yellow and thread-like dark brown laminae. They are usually irregular, crinkled, occasionally convoluted and exhibit angular terminations. Microunconformities with onlapping relationship between bands of cortical laminae are also observed in many pisoids (Pl.1g). The bright orange laminae are commonly thicker than the dark ones, but being non-isopachous, mostly goethitic in composition and appear to be developed at the expense of the dark laminae (Pl.1f&h). In some cortices the dark thread-like laminae are closely packed in such a way that they lose their individuality and form a thick dark zone. The cores of most micropisoids are massive and cracked micronodules having dark red to brown colour and almost of hematitic composition or occasionally being of amorphous iron (Pl.1h). Micropisoids with two or three cores of micronodules or with nucleus of quartz grains are rarely recorded. The ferriferous intraclasts are angular, shapeless and internally massive grains, being

almost of hematitic and goethitic composition. They are orthic particles and identical in both fabric and shape to the *in-situ* fragmented glauconite grains dominating in the glauconitic sandstone facies (Pl.2a&b). The space between microglauconites, intraclasts and quartz grains are irregular and occupied by porous and earthy brown amorphous iron mud matrix with abundant disseminated goethite crystallites. The amorphous iron-matrix shows a faint greenish tint (Pl.1f) and represents the insoluble residue of the precursor iron-rich glauconitic mud from which the orthic particles (microglauconites and intraclasts) have been developed. The microprobe analyses of cores and cortical zones of micropisoids, massive micronodules as well as pore-filling ferruginous matrix and cement (Fig.6), show general enrichment with Al (10.4-21.7 %) and Si (10.1-19.1 %).

Interpretation

The nodular and boudinage bed-geometry of this facies and its essential constituents of welded and anastomosed ferriferous micronodules, micropisoids and fitted intraclasts indicate that this ironstone type is formed *in-situ* and represents a lateritic weathering product (Fig.5). The development of well-defined nodules and pisoids is considered as an ultimate stage of plasmic concentration and differentiation of the original s-matrix in soils and laterites (Brewer and Sleeman, 1964; Nahon, 1995). At this stage of glauconitization, the primary fabric and composition of the original host rock almost completely alter or vanish (Nahon *et al.*, 1980; Ambrosi *et al.*, 1986). This may explain the missing of any inherited depositional features or components in this ironstone facies, except for the amorphous iron residue in the alveolar voids and the durable quartz grains. The latter also suffer intensive corrosion and partial replacement by iron-oxide minerals. However, the stratigraphic position of this facies, its downward grading into ferruginous glauconitic sandstone and the occurrence of quartz grains and glauconite ghosts may suggest that argillaceous glauconitic sandstones/ mudstones were probably the parent sediments of such ironstone type. Similar to the underlying facies, this parent clastics accumulated in the tidal flat environment, that experienced a considerable periods of exposure and lateritic weathering.

3.3. Parautochthonous microgranular pack/grain-ironstone (PMI)

Description

This ironstone facies type is characterized by an enrichment with ferriferous allochems and authigenic goethite cement as well as a remarkable decrease in the detrital quartz grains (Pl.2c). Its content of iron reaches to 32 % (Fig.4). The facies constitutes thin beds (5-15 cm thick) that rest with erosional contact on the autochthonous microglauconular ironstone facies. The beds are rippled and commonly bioturbated with *Thalassanoides* (Pl.2d). The rock is identical, in composition, with the underlying autochthonous microglauconular facies, but displays different depositional fabrics and textures. It is a grain-supported packstone to grainstone consisting entirely of ferriferous micronodules, micropisoids and intraclasts with subordinate quartz grains (Pl.2c). The ferriferous particles are almost worn, rounded to subrounded, well sorted and exhibit tangential to free (floating) contacts (Pl.2c). These grains range, in size, from fine- to medium- and occasionally coarse-sand. They are mainly composed of goethite and hematite enclosing, in parts, amorphous iron oxyhydroxides. The interparticle voids are completely occluded with a dark reddish brown iron-rich matrix, being usually replaced by massive cement of goethite and hematite or amalgamated goethite crystals displaying distinct circular, square and polygonal cross sectional shapes (Pl.2c).

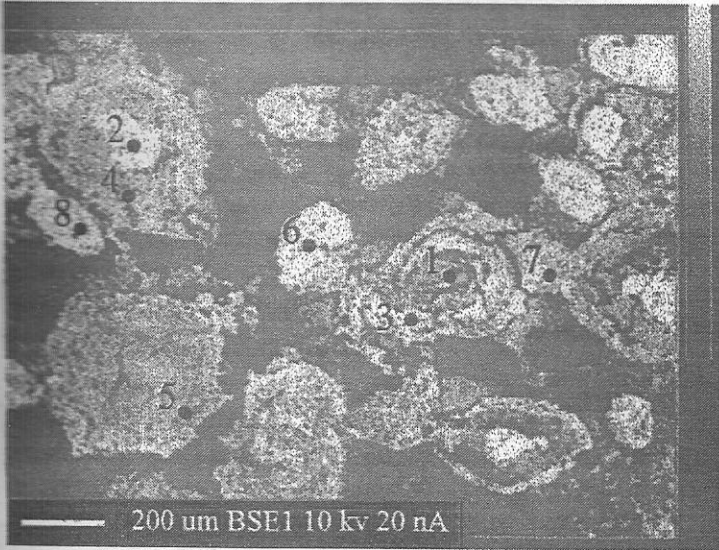
Interpretation

The grain-supported fabric, rippled bedform and *Thalassanoides* echinofossils of this facies indicate its accumulation in very shallow, well-oxygenated marine water under effective hydrodynamic conditions (Fig.5). The well-sorted and good-rounded nature of the rock allochems reflects episodic erosion of the sea floor and a considerable reworking. The remarkable decrease of the detrital quartz grains, relative to the underlying facies, as well as the common bioturbation point to that, the ferriferous particles reworked and slowly accumulated under conditions of a considerable cessation of allochthonous clastics (Burkhalter, 1995; Donaldson *et al.*, 1999). Such depositional regime suggests that this facies represents storm- or transgressive- lag deposits; their allochems (intraclasts and microglauconites) are scoured and reworked with/ or without local transportation from the lateritic autochthonous ironstone facies.

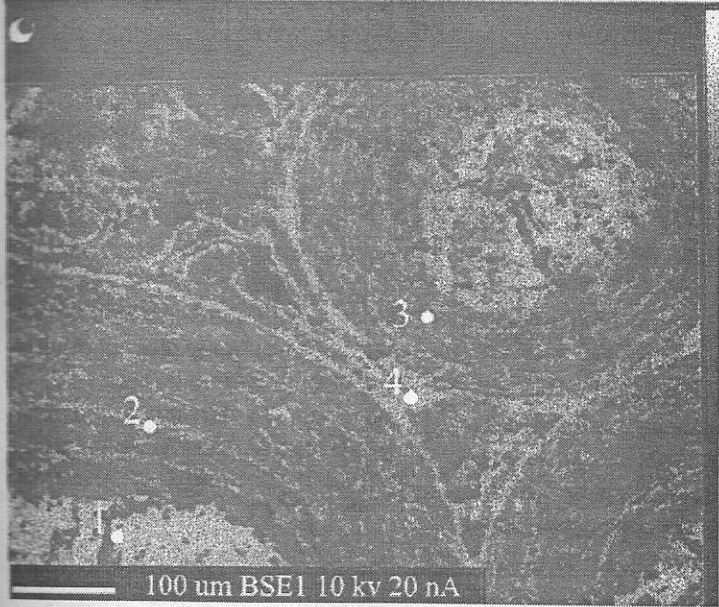
3.4. Microglauconular ooidal grain-ironstone (MOI)

Description

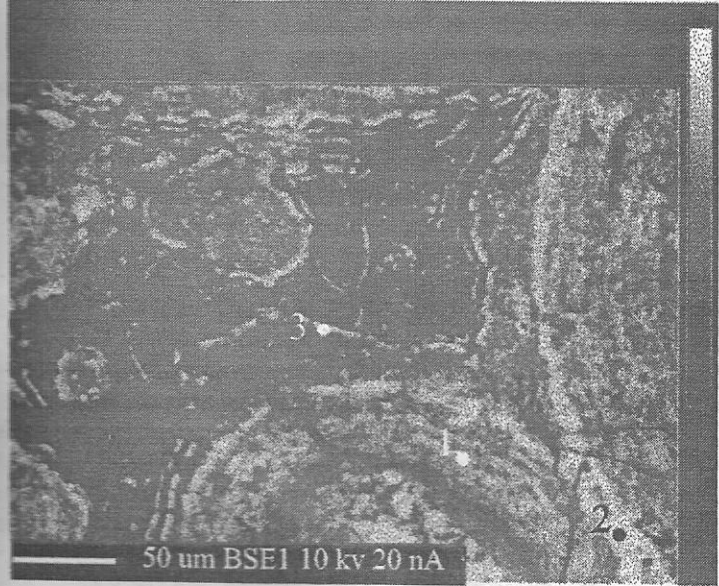
A single bed of this proper ooidal ironstone facies (Fe: 42.0 %) is only recorded at the base of the ironstone hosting interval (Fig.4). It mantles the transgressive surface of the lower retrogradational sequence of the Hawashiya Formation. The bed reaches up to 25 cm thick, starts with erosive sole and terminates with a ripple top. It is internally massive and penetrated with short vertical *Skolithos* tubes. The facies is yellowish to reddish brown, very well sorted and medium to coarse-grained grain-ironstone (Pl.2e&f). It is composed mainly of ferri-oids with some ferri-micronodules and intraclasts as well as rounded and subangular quartz grains (Pl.2e&f). The micronodules and intraclasts serve most commonly as nucleus for ferri-oids and less commonly as framework components. They are almost of hematite and goethite composition. The pervasive grain size of ferri-oids range from 0.5 – 3 mm. They are well sorted; good rounded and show frequently tangential grain contact. Most of them have two or three cortical zones; an inner dark zone and an outer bright one. Superficial ooids with



	1	2	3	4	5	6	7	8
Fe	53.23	69.44	64.57	15.15	46.25	48.86	47.86	65.28
Mn	01.44	00.06	00.92	01.20	01.41	00.47	06.76	00.00
Ca	00.18	00.16	00.39	01.50	00.33	00.75	00.49	00.29
K	00.00	00.47	00.07	00.87	00.00	00.44	00.86	00.00
Na	03.19	02.55	01.47	07.66	11.98	05.41	03.42	00.94
Mg	07.14	05.02	04.45	08.04	08.23	08.84	07.81	06.14
Al	21.74	11.58	10.42	13.55	20.65	15.37	17.96	14.23
Si	11.53	08.57	16.26	51.33	10.13	19.06	13.65	11.82
P	01.55	02.15	01.45	00.70	01.02	00.80	01.19	01.30



	1	2	3	4
Fe	95.45	92.56	93.10	95.44
Mn	00.72	00.41	00.34	00.03
Ca	00.30	00.40	00.55	00.46
K	00.05	00.36	00.05	00.00
Na	00.07	01.09	00.01	00.14
Mg	00.04	00.57	00.43	00.12
Al	02.07	03.11	03.79	02.66
Si	00.82	01.15	01.34	00.67
P	00.49	00.35	00.39	00.48



	1	2	3
Fe	94.39	54.03	50.16
Mn	00.30	00.40	00.72
Ca	00.41	00.86	00.80
K	00.00	00.00	00.08
Na	00.00	02.83	01.09
Mg	00.42	05.03	05.65
Al	02.96	18.08	17.77
Si	01.18	17.34	12.67
P	00.34	01.43	01.06

Fig.6. Distribution of the main chemical elements detected along the microprobean analyses of the cores and cortical zones of microglaeboles and the intergranular spaces.

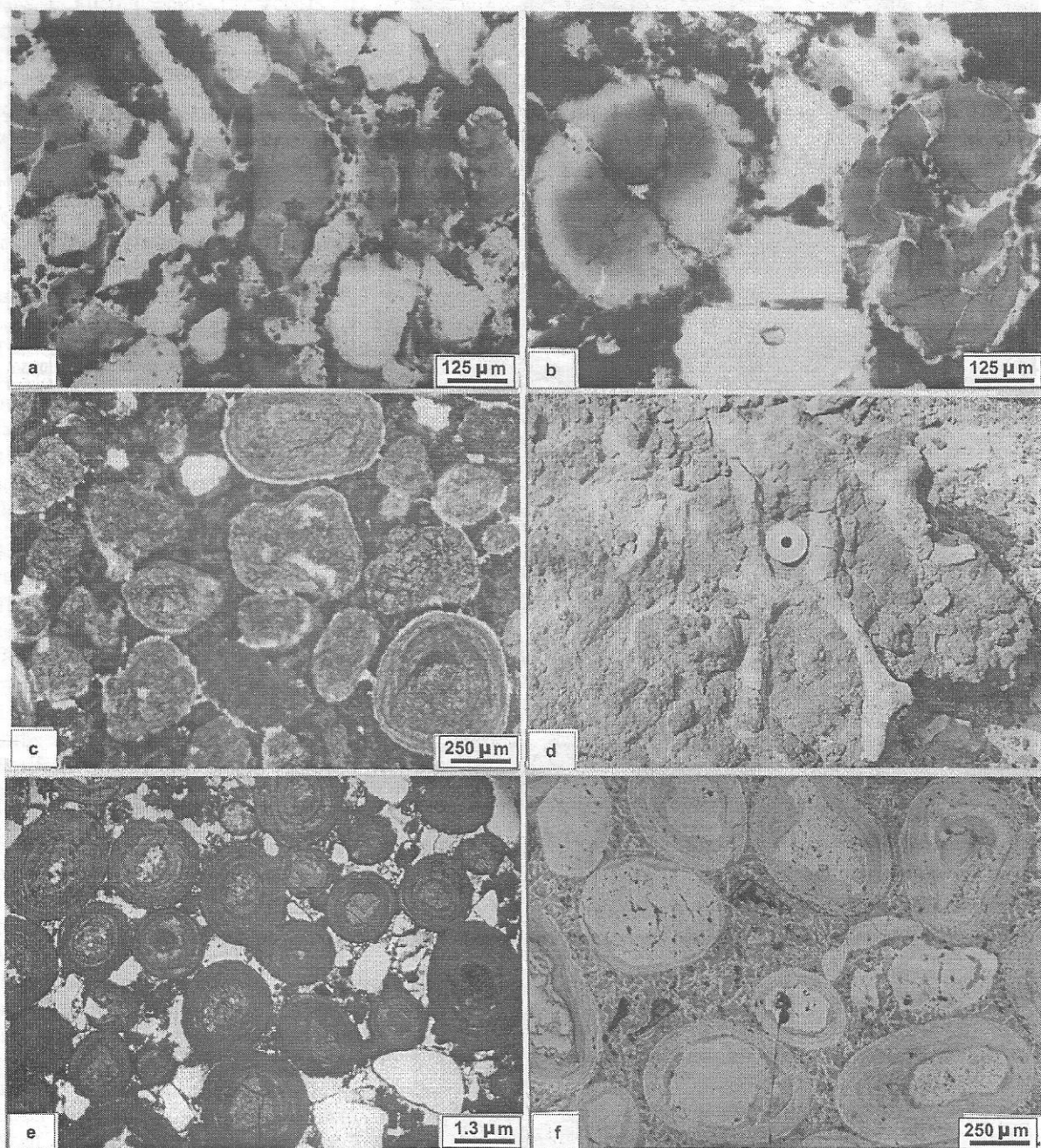


Plate 2

(a): Slightly oxidized and in situ fragmented glauconitic mud giving fitted angular glauconite fragments, GSF (PPL). (b): AMI facies with massive ferriferous intraclasts exhibiting bi- and tri-lobate form that is identical with the glauconite fragments of GSF (PPL). (c): Rounded and well sorted ferriferous micropisoids, micropisoids and intraclasts with little quartz form AMI facies. Notice the circular, square and polygonal crystallites of goethite surrounding remnant clots of the original amorphous iron mud matrix. (PPL). (d): *Thalassanoids* burrows penetrate and homogenize the beds of the AMI facies. (e & f): well sorted MOI facies rich in ferriferous ooids with some microglauclules and quartz. Notice the sharp and irregular boundary between the inner cortical zone and the core, and the distinct inner dark and outer bright cortical zones (arrow). Fig. e (PPL), Fig. f (polished sample, PPL).

very thin dark cortical rind are also scarcely observed. The cortical zones are either thrombolitic or massive (original depositional fabric) or being most commonly with fine discontinuous laminations (diagenetic texture) of intermingling bright orange thicker laminae and fine dark threads. The ferriferous framework grains sit in a brown amorphous iron mud matrix being highly dissected and surrounded by authigenic hematite and goethite irregular laminae forming a network like texture. Colloform goethite cement filling some pore spaces also occurs.

Interpretation

Except for the predominance of the proper ferri-oids in the composition of this facies; its depositional texture, fabric, structure and bed geometry resembles to a great extent those of the parautochthonous PMI facies (No.3.3). Thus it is also accumulated in very shallow water subjected to episodic storm reworking and local transportation (Fig.5). It may represent lag deposits concentrated on the transgressive surface with the onset of the lower Hawashiya sea incursion. The grain supported, very well sorted and good rounded texture of the ooids and scarcity of detritus grains suggest a near complete clastic starvation and increased hydraulic energy during formation (Donaldson *et al.* 1999).

DISCUSSION AND IRONSTONE GENESIS

Despite numerous studies have dealt with sedimentary ironstones, particularly the oolitic types, it is not easy to draw a unique or a firm depositional and diagenetic model regarding its genesis. Three definite principal questions currently arise in any attempt for the scenario of oolitic ironstone formation. These are:

1. What is the precursor iron-rich substance or mineral for the goethitic, hematitic and chamositic coated grains (ooids, pisoids or oncoids)? Is it a gel-like hydrous (Fe&Al) silicates (Harder, 1989) or a mixture of clays and Fe-hydroxides (Bhattacharyya and Kakimoto, 1982; El Aref *et al.*, 1996) or glauconite (Parron and Nahon, 1980) or odinite (Bailey, 1988) or bertherine (Young, 1989) or colloids of goethite (Gehring, 1989).
2. Do the ferriferous ooids and oolitic ironstones represent autochthonous weathering products of lateritic soils (Nahon *et al.*, 1980) or originally autochthonous/para-autochthonous marine deposits (Gygi, 1981; Burkhalter, 1995; El Aref *et al.*, 1996; Helba *et al.*, 2001) or allochthonous marine accumulations derived from lateritic hinterlands (Siehl and Thein, 1989)?
3. What is the mechanism of oolitization?. Is it a glaebulization *in situ* (Nahon, 1995) or a mechanical accretion (Bhattacharyya and Kakimoto, 1982; El Aref *et al.*, 1996) or a microbial accretion (Dahanayake *et al.*, 1985; Helba *et al.*, 2001) ?

In the context of those questions and related alternatives, together with the collected field and microscopic observations, the genesis and development of Wadi Qena ironstones can be discussed as follows:

1. Precursor substances

As revealed above, the Wadi Qena ironstones comprise four main facies types (BSI, AMI, PMI and MOI, Fig.3). The autochthonous microglaeubular ironstone (AMI) is the essential and the most abundant type. The scouring of this rock type and the reworking and sorting of its allochems (orthic microglaeubules and intraclasts) via storms or with marine floods result in the accumulation of the parautochthonous microglaeubular- or ooidal- pack/grain-ironstone types. So, the autochthonous concretionary ironstone is considered as the mother rock for the grain-supported parautochthonous ironstone facies (PMI, MOI). On the other hand, the mega- and microscopic features (e.g. mottling, boudinage form, welded microglaeubules, alveolar voids and crackling) of the concretionary ironstone mother rock, indicate that it is accreted *in situ* and represents alteration or weathering products of pre-existing sediments. In outcrops, the distinct transitional contact between this ironstone and the underlying slightly ferruginous glauconite-rich sandstones or sandy mudstones, suggests that these glauconitic clastics represent the altered parent sediments. These sediments may be mixed with amorphous Fe oxyhydroxides that occurred in the depositional medium as colloids. This consideration can be evident by:

- 1) The presence of glauconite ghosts with authigenic kaolinite or quartz in alveolar voids in both ferriferous allochems and matrix. These alveolar voids and its contents represent remnants of the consumed precursor glauconitic sediments,
- 2) The close morphologic similarity between the *in-situ* fragmented intraclasts of proper glauconite in the glauconitic sandstone facies and the orthic ferriferous intraclasts of the autochthonous ironstone facies (Pl. 2 a&b). Both of which mostly show internal curved cracks and bi- or tri-lobate forms, and
- 3) The goethite and hematite forming microglaeubules and intraclasts are relatively enriched with Al (10.4-21.7 %, Fig. 6). High Al-substitution (10-15 %) in goethite or hematite characterizes the ferriferous ooids and pisoids that formed in lateritic environments (Parron and Nahon, 1980; Maynard, 1986; Siehl and Thein, 1989), and those developed at the expense of glauconite particles (Parron and Nahon, 1980;

Nahon *et al.*, 1980). The *in-situ* alteration and transformation of glauconite or glauconitic clastics into massive or oolitic ironstones have been documented in several studies (e.g. El Sharkawi and Khalil, 1977; Parron and Nahon, 1980; Mesaed and Surour, 1999).

2. Ferriferous allochems (Site and mechanism of formation)

Micronodules, micropisoids, intraclasts, and ooids are the ferriferous allochems forming the frameworks of the Wadi Qena ironstone facies. They are composed mainly of admixture of amorphous Fe hydroxides, goethite and hematite, either as patches of submicroscopic scales or crystals or as alternating discontinuous concentric laminae. The intraclasts and microglauconites are originally formed *in-situ*, via an incongruent alteration and transformation of glauconite. The primary shape and boundaries of these particles are almost intimately controlled by the drying cracks dissecting the glauconitic matrix, cement or lenses in the parent glauconitic clastics. However, in the parautochthonous ironstone facies, a modification of the primary form and size with enhancement of roundness and sorting occurred due to the continuous reworking. The *in-situ* growth of the ferriferous microglauconites and intraclasts is evident by:

- a) Their welded and anastomosed nature with polygonal fitting and reciprocal contacts (Pl.1e). They are similar to the *in-situ* grown caliche pisoids of Dunham (1969),
- b) The hazy and corrosive contacts between the cores and cortical laminae of micropisoids (Pl.1e&f),
- c) The reverse relationship between the thickness of cortices and thickness of core. This relationship and the hazy contacts substantiate that the cortices had developed diagenetically in the expense of the cores,
- d) The discontinuous, non-isopachous and interfering nature of the different laminae constituting cortices. This suggests that, the growth of each cortical laminae is not always isotropic in three dimensions, but that it can display a preferred direction at one instant or another of its history (Nahon, 1995), and
- e) The common kinking and angular terminations of the cortical laminae (Pl.1e&f). This sharp-angle geometry proves a growth *in-situ*, without any local rotation and wearing of the particles.

Paragenetically, the orthic micronodules and intraclasts consisting predominantly of amorphous Fe hydroxides may represent the early alteration product of glauconite in the parent clastics. They conform the shape of the *in-situ* cracked and accentuated glauconite particles, and enclose remnants of glauconite ghosts. The micropisoids formed mostly of goethite and/or hematite represents the advanced product of intensive weathering and alteration. They appear clearly to be evolved from those massive micronodules and intraclasts as attested by the preservation of amorphous Fe hydroxides in their cortices and cores. The growth of pisolitic concretions (with oolitic structure) from massive nodules (with asepis structure) indicates the transition in the alteration stages from moderate to strong differentiation and concentration of the weathering plasma in the weathering or lateritic profiles (Nahon *et al.* 1980; Nahon, 1995). The distinct corrosive, hazy and gradational boundaries between cortices and amorphous iron cores of most micropisoids suggest that the individualization of the cortical laminae occurred via a centripetal concentric growth of goethite and/or hematite laminae in the expense of amorphous Fe hydroxides. A consequence to this process, the micronodules and intraclasts are consumed and their remnants appear as nuclei of the micropisoids. In the micropisoids, the thickness and frequency of hematite, goethite and amorphous Fe hydroxide laminae, relative to each other, vary from particle to another and even in different zones of the same micropisoid. That variation is related to the different degrees of dehydration and oxidation even in the microscopic spots. With increasing oxidation, the hematite laminae evolve from goethite, which in turn develop in the expense of amorphous iron. In some cases, the growth of goethite or hematite becomes pervasive to the extent that it could destroy or homogenize the concentric structure of the micropisoid. The latter gives rise again to massive micronodules or intraclasts, which in this case consist essentially of goethite and/or hematite with or without traces of amorphous Fe hydroxides. The free Al and Si that delivered in pore water from glauconite transformation into iron oxides are in parts, reprecipitated in the alveolar and intergranular voids as authigenic kaolinite and quartz. Also, some of the free Al are nano-transferred and substituted the iron-oxides minerals, forming Al-rich goethite and hematite.

Contrasting with the *in-situ* formed micropisoids, the recognized ferriferous ooids display distinctive features that indicate a centrifugal accretion of their primary cortices (i.e. a successive outward building of the cortical zones upon nucleus). The accretion might be induced mechanically, biogenically or through adsorption process. The ferriferous ooids invariably possess cores; either of micropisoids, micronodules, intraclasts or their fragments, which were derived and reworked from the pre-existing or adjacent autochthonous/parautochthonous microglauconular ironstone facies. The distinctive features substantiating the outward accretion of the cortical zones comprise: a) the very sharp contact between the cores and the enveloping inner cortical zones as well as between the different zones of cortical laminae (Pl.2e&f). This contrasts with the orthic micropisoids in which the core-cortex contact is hazy indicating a growth of the cortex in the expense of the core, b) the nonlapping and non-isopachous geometry of the inner cortical zone in such that, it is thicker at the recessed core margins than at the protruded ones (Pl.2 f). Such geometry reflects a filling on a pre-existing substrate with a microrelief, c) there is no intimate relationship between the core size and cortex thickness such as the reverse relationship

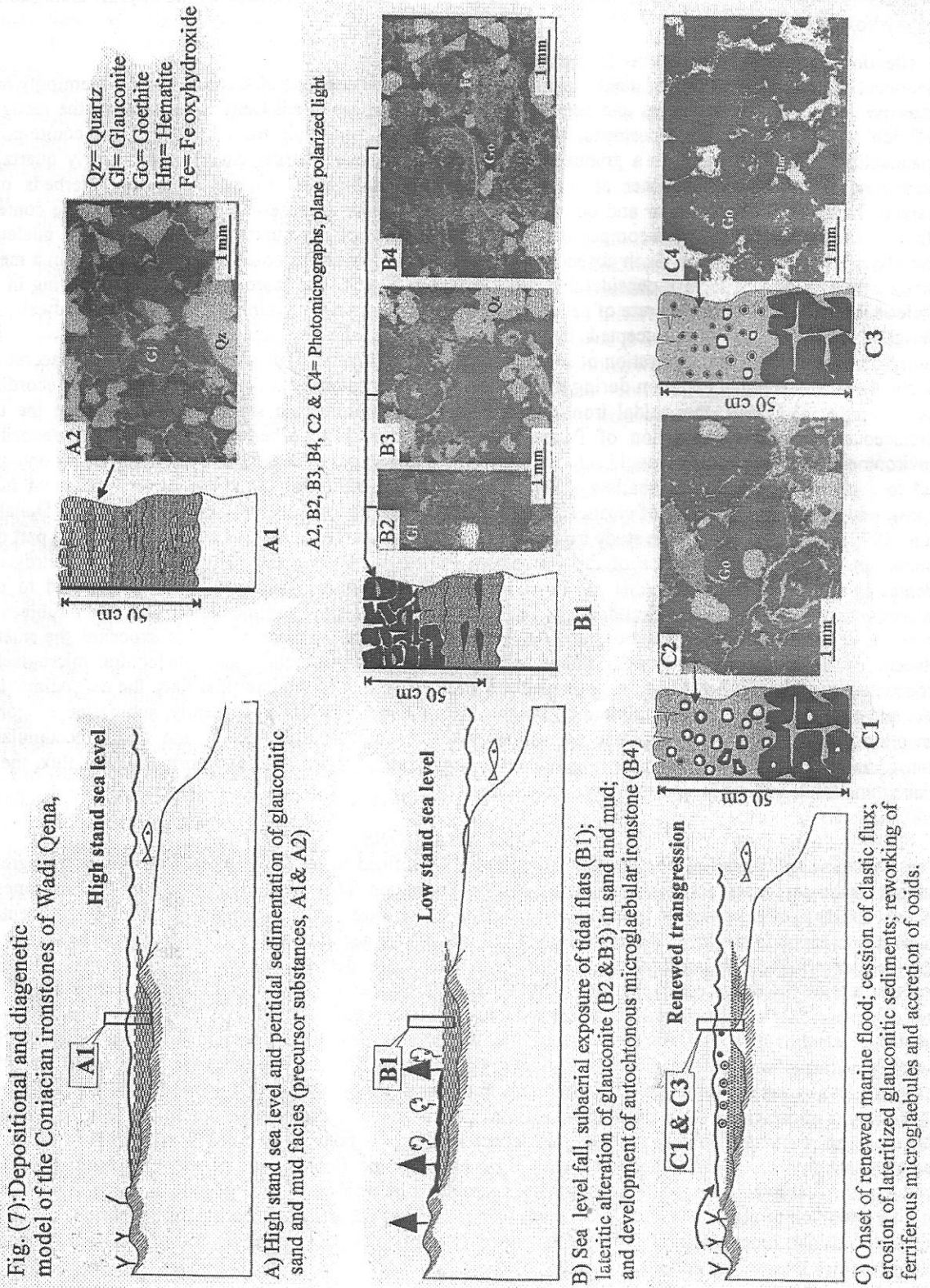
characterizing the orthic pisoids, and d) the smooth rounded nature of the boundaries between cortical zones and of the external margin of ooids reflecting their rolling during accretion. The accreted ooid cortices consist primarily of a single or two cortical envelopes, which are originally composed of massive or thrombolitic amorphous Fe-oxyhydroxides. Although, these primarily massive envelopes are syndepositionally accreted (mechanically or biogenically?), their internal individualization into intermingling laminae of goethite and hematite is diagenetic in origin and developed through dehydration and oxidation of the original amorphous Fe-oxyhydroxide composition.

3. Clastic starvation and ironstone formation

Sea-level changes and the concomitant variation in both of clastic supply and accommodation seemingly had an effective impact on the processes and conditions for developing the Wadi Qena ironstones. In the recognized peritidal cycles hosting the ironstones, the common upward transition from relatively glauconite-poor to glauconite-rich clastics suggests a gradual cessation in the input of detrital clastics (particularly quartz) and concentration of glauconite either as allogenic matrix or authigenic cement. Also, the interbeds of the parautochthonous microglauconitic and ooidal ironstone facies show an observable diminution in the content of detrital quartz (relative to the encompassing facies) and absence of any quartz grains serving as a nucleus for their ferri-ferrous coated grains. Such absence indicates that, the ferri-ferrous ooids had been accreted in a medium being barren or starved from a considerable detritus supply (Fig.5). The thorough biogenic burrowing in these facies substantiates also the low rate of net sediment accumulation under diminished clastic flux (Kidwell, 1991; Wright, 1986). It has been accepted by many authors (e.g. Einsele and Bayer, 1991; Kidwell, 1991; Burkhalter, 1995) that, a concentration of some minerals like authigenic glauconite, phosphates and accretion of ferri-ferrous ooids is much common during the periods of syndepositional clastic starvation (Fig.5). According to Donaldson et al (1999), the ooidal ironstone represents the most clastic starved environment in the upper Cretaceous Bad Heart Formation of Peace River Arch area, NW Alberta, Canada. In the depositional environments, clastic starvation could achieve either in the late stages of regression, when limited accommodation led to a clastic by passing of shallow shelves (Macquaker et al, 1996), or in the earliest phase of marine transgression, due to a ponding of clastic detritus in alluvial and coastal areas (Christie-Blick, 1991; Donaldson et al, 1999). As shown before, the study ironstones and hosting glauconitic clastics constitute the basal part of the Coniacian transgressive sequence of the Hawashiya Formation. During the early stages of the retrograding Coniacian shoreline, the glauconitic clastics accumulated in shallowing-upward cycles along mid to upper intertidal flats (Fig.7A). The intertidal flats are usually areas of slow sedimentation and often subjected to intermittent periods of subaerial exposures (Weimer et al, 1982). During these periods of exposure, the emergent glauconitic sediments are weathered, altered and transformed into autochthonous glauconitic microglauconitic ironstones (Fig.7B). With the beginning of renewed marine flooding of the intertidal flats, the net sedimentation rate and clastic supply are often minimum (Nummedal and Swift, 1987). Consequently, submarine erosion and reworking of autochthonous ironstone as well as onset of ooid accretion occur, and finally accumulate as transgressive ferri-ferrous lag deposits (Fig.7C). After stabilization of sea level and normal clastic flux, the host glauconitic sands and muds start the deposition again (Fig.7 A).

CONCLUSIONS

The Coniacian ironstones of north Wadi Qena area are confined to the basal part of the lower transgressive (mixed clastic-carbonate) succession of the Hawashiya Formation. They are hosted in glauconitic sandstones and mudstones that stack vertically in small-scale shallowing-upward cycles representing peritidal sedimentation under a fluctuation in sea level, sediment supply and rate of sedimentation (Fig.5). The ironstone beds (5-40 cm, thick) either terminate the peritidal cycles or delineate their bases, demarcating the peak of sea level fall and the onset of marine floods, respectively. Four main types of ironstones are recognized relying on their depositional and diagenetic fabrics, which reflect different modes, processes and conditions of formation. These types are: bioclastic sandy mud- to wacke-ironstone; autochthonous ironstone; parautochthonous microglauconitic pack grain-ironstone; and microglauconitic ooidal grain-ironstone. The last two types are richer in Fe content and relatively less in gangue minerals. They represent transgressive lag deposits that derived from the first type via its erosion, reworking and subsequent accumulation under effective hydrodynamic conditions (Fig.7C). Their net accumulation rate was relatively low and their concentration was favored by a nearly starvation in the detritus sediment supply, which often prevailed with a renewed marine flooding. In contrary to those depositional products, the first ironstone type "autochthonous microglauconitic ironstone" is diagenetic in origin. It represents a lateritic alteration of glauconitic sands and muds that exposed to subaerial weathering during periods of sea level fall and tidal flat emergence (Fig. 7B). Glauconite as matrix, cement or lenses mixed with amorphous Fe-oxyhydroxides imposed as colloids; represent the precursor substances for the Wadi Qena ironstones. Sea level fall, subaerial lateritic weathering, renewed marine flooding, marine -erosion, reworking and clastic starvation were the main genetic conditions and processes controlled the formation of the ironstones.



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انقطاع المد الفتاتي والتحول اللاتيريتي أثناء الترسيب: كعناصر أساسية ساعدت في تكوين حجر الحديد البتروخي في التتابع الرسوبي للزمن الكوني، شمال وادي فنا، الصحراء الشرقية، مصر

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الملخص

يتناول البحث دراسة وتوصيف الحجر الحديدي البتروخي المكتشف داخل التتابع الرسوبي للزمن الكوني والمنكشف بشمال وادي فنا بالصحراء الشرقية. تهدف الدراسة على استنتاج مسار نشأة مكونات الحجر الحديدي البتروخي وكيفية ترسيبها مع تغير الظروف الترسيبية وعمليات ما بعد الترسيب التي تحكم في إنتاجها.

وقد ظهرت الدراسة الحقلية والميكروسكوبية المدعمة بالتحاليل الكيميائية أن طبقات الحجر الحديدي البتروخي بوادي فنا تتواجد ضمن التتابع الرسوبي لمكون "حواشيه" والذي ترسب في بيئة بحرية تتراوح من رصيف بحري ضحل إلى حزام شاطئي. ويتكون الحجر الحديدي المنروس من نوعين أساسيين من السحنات الحديدية الرسوبية وهى: سحنات حجر حديدي أصلية (autochthonous) وسحنات مشتقة ومنقولة (para- autochthonous). وسحنات حجر الحديد الأصلية هي التي تكونت بإمكانها داخل الحوض الترسيبي ونشأت من عمليات تحول وأكسدة لحبيبات معدن الجلوكونيت المترسب ضمن مكونات رواسب الخبز والرمال الطيني في فترات انحصار المد الفتاتي بحوض الترسيب. هذا وقد تمت الأكسدة والتغيرات اللاتيريتية لحبيبات معدن الجلوكونيت أثناء فترات متقطعة من انحصار وهبوط مستوى سطح البحر مع انكشاف حوض الترسيب لعمليات التجوية مكونة نرة لاهوائية غنية بمكونات جسيمه (massive nodules) وحبيبات بتروخية ذات حواف متلاحمة ومتداخلة. يتراوح تركيب المكونات والحبيبات بتروخية من جلوكونيت ضعيف التأكسد وجلوكونيت حديدي عالي التأكسد إلى جوتيت به بقايا من الجلوكونيت. وعلى النقيض تتميز سحنات حجر الحديد المشتقة والمنقولة بدرجة جيدة من تماثل الحجم الحبيبي والمنكون من مكونات وحبيبات بتروخية عالية البرى والاستدارة وذو نسيج مدعم بالحبيبات (grain-supported) وفقير أو خالي من الفتات لغريني (matrix-supported) وتتركب أغلبها من الجوتيت والهيماتيت. وطبقات هذه السحنة تظهر تطبيق كاذب وعلامات نيم مع تركيب حورية من نوع (Skolithos and Thalassanoides) مشيرة إلى ترسيبها تحت تأثير تيارات وأمواج بحرية على أرضية متحركة (mobile substrate). وتمثل هذه السحنة الناتج الترسيبي من عمليات تعرية وتفتيت وكس لطبقات النوع الأول من السحنات مع تداول (reworking) وبرى ونقل محدود لمكونات هذه السحنات ثم ترسيبها تحت ظروف هيدروديناميكية نشطة أثناء فترات تقدم البحر (transgressive events) على الحوض الترسيبي.

وقد أظهرت الدراسة تغير انحصار المد الفتاتي (clastic starvation) وكذا عمليات التغير اللاتيريتي في إنتاج الحجر الحديدي بتروخي من أثناء ترسيب رواسب فتاتيه غنية بمعدن الجلوكونيت.